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TWENTY-NINE MONTHS OF SOLAR RADIATION AT TUCSON, ARIZ.

By GEORGE E. DAVIS AND JOSEPH L. MCCARTHY

[From the laboratories of the Desert Sanatorium and Institute of Research, Tucson, Ariz.]

The intensities of direct solar radiation at wave-lengths 0.50μ and 0.32μ are recorded daily at Tucson at the Desert Sanatorium and Institute of Research. The records are automatically traced on photographic plates by a Pettit solar radiometer. In the period of 29 months from February, 1930, to June, 1932, inclusive, approximately 500 such plates were chosen as satisfactory for measurement. From the measurements, values of intensity of radiation were computed in absolute units for the hours 9:00 a. m., 12:00 noon, and 3:00 p. m., local apparent time. Only values for an unclouded sun were included. There were 460 satisfactory records at 9:00 a. m., 448 at 12:00 noon, and 370 at 3:00 p. m. Corresponding values of air temperature, humidity, barometric pressure, and atmospheric haze were measured throughout the period of 29 months.

The elevation at the point of observation is approximately 2,470 feet. In every direction stretches a fairly level, semiarid plain covered with creosote bush, mesquite, cacti, and other desert plants. The plain is almost completely inclosed by high mountains. These lie approximately 7 miles north of the point of observation, 14 miles east, 45 miles south, and 7 miles west. The prevailing direction of motion of the surface winds is northwest.

INSTRUMENTS AND METHODS

The Pettit solar radiometer has been described by Pettit (**1, 2**) and by Davis (**3**). Essentially this instrument consists of a silvered quartz lens and a gilded glass lens, mounted on a disk which rotates at intervals of one minute, the lenses forming images of the sun alternately upon the receivers of a compensated thermocouple which is connected with a sensitive galvanometer. The silvered quartz lens transmits a narrow band of ultraviolet radiation with maximal intensity at λ 0.32μ, while the gilded lens transmits a broad band of radiation with maximal intensity at λ 0.50μ in the green region of the spectrum. The galvanometer deflections are recorded on a moving photographic plate, together with transverse lines indicating the hour angle at intervals of one hour. The deflections are proportional to the intensities of the rays transmitted by the lenses.

The radiometer was calibrated by making simultaneous measurements of solar radiation by means of an entirely separate instrumental assemblage. This consisted of a Bausch & Lomb quartz monochromator fitted with a special detachable thermopile head; a specially constructed photometer box with internal shields, mounted on a base to which the monochromator also could be attached; an incandescent lamp calibrated by the Bureau of Standards; a very sensitive D'Arsonval galvanometer; and accessory instruments for measuring current, resistance, etc. The thermopile, detached from the monochromator and carrying its own entrance slit, was first calibrated by measuring the voltage generated when radiation of known intensity from the standard lamp fell upon the receiving strip. A separate measurement was made to determine the absorption of the quartz window of the thermopile case for long-wave radiation from the standard lamp, and corrections were made for such absorption. The thermopile head then was attached to the quartz monochromator, which was mounted on the base carrying the photometer box. The base was supported in such a manner that the photometer box could be kept pointed directly toward the sun. The radiation passed through the box and fell directly upon the slit of the monochromator. The thermopile was connected with the sensitive galvanometer, which had a scale distance of 776 cm. Readings were made at intervals of 50A throughout spectral ranges extending from λ 3050 to 3350A and from λ 4850 to 5150A. At each position the width of the exit slit of the monochromator, which determined the amount of radiation falling upon the thermopile, was adjusted to include exactly 100A of the spectrum. The data thus obtained were plotted and the radiant intensity at λ 0.32 and 0.50μ computed from values taken from the curves. In the computations, corrections were made for the radiation losses in the quartz monochromator, data on which were furnished by Bausch & Lomb. Having determined the radiant intensities in this manner, comparison with the galvanometer deflections simultaneously recorded by the Pettit solar radiometer gave calibration factors which, multiplied by the deflections, give the intensities at wave-lengths 0.50μ and 0.32μ, in absolute units (here watts/100 A/m^2). Throughout the work of calibration great care was taken to insure accurate results.

Measurements of relative atmospheric humidity were made by means of a sling psychromator with wet and dry bulbs. The absolute humidity was calculated from the air temperature and the relative humidity, by reference to tabulated values of mass of water vapor in saturated air. Barometric readings were obtained from a mercury barometer. Temperatures were measured with a mercury thermometer.

Observations of atmospheric haze were made by eye, the observer looking toward the foothills of the Santa Catalina Mountains lying some 8 or 9 miles distant in a direction a little west of north. Haze appears gray or blue-gray against the distant hills and adjacent plains. When observed, it was recorded as "very faint," "faint," "medium dense," "dense," or "very dense." Such estimations are very rough. However, they make it possible to obtain some idea of the effect of haze upon the intensity of the solar radiation.

RADIOMETRIC DATA

Since the numbers of values of radiant intensity obtained in the various months differ widely, the monthly averages are by no means of equal weight. Therefore it was decided to average the data in groups of 10 consecutive values each, each group representing 10 days but not necessarily 10 consecutive days. With this grouping all the average values are of equal weight. Each average is plotted at the average date represented by the 10 values. We believe that this method of averaging and plotting gives a more reliable representation of the actual march of radiant intensity than does the usual method of plotting monthly averages, in case the number and distribution of daily values vary markedly from month to month.

relation, $-\log_{10}T = CM$, where T is the atmospheric transmission, C is a constant, and M is the air mass. The value of C was chosen to make the maxima and minima agree approximately with the average maxima and minima of the corresponding intensity curves. We shall refer to these dotted curves as the "curves of average atmospheric transmission."

The most striking features of these radiation curves are their irregularities. Marked variations in intensity occur at irregular intervals throughout the year. We believe that these variations are not due, to any great extent, to errors of measurement. This point will be discussed later and some partial explanations of the irregularities suggested.

Considering individually the curves for green radiation, $\lambda 0.50\mu$, it is seen that the general trend at 12:00 noon

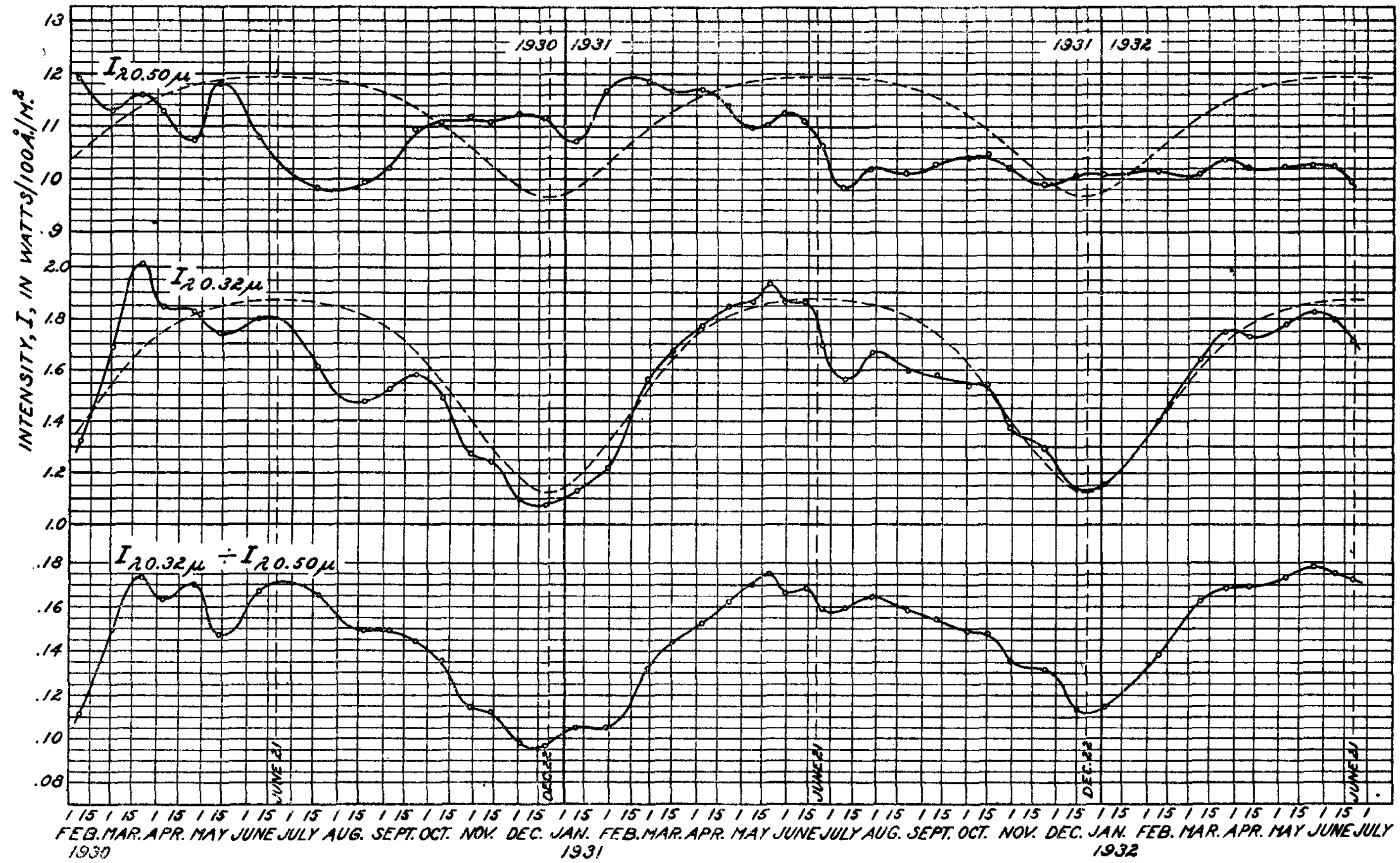

FIGURE 1.—Intensity of solar radiation at wave lengths 0.50μ and 0.32μ, at 12:00 noon, local apparent time. Each plotted point is the average of 10 daily values. The dotted lines are the calculated curves of average atmospheric transmission.[1] The lower curve represents the ratios of the intensity at $\lambda 0.32\mu$ to that at $\lambda 0.50\mu$.

In Figures 1 and 2 the average values of intensity, in absolute units, are plotted, together with the ratios of the intensity at $\lambda 0.32\mu$ to the intensity at $\lambda 0.50\mu$ (lower curves). The values for 12:00 noon (hour angle zero) are shown in Figure 1, the values for 9:00 a. m. and 3:00 p. m. (hour angles -3 and $+3$) in Figure 2. The data of Figures 1 and 2 are represented also by the curves of Figure 3, which show the 2 or 3 year averages. These averages are found from values taken from the smooth curves. Also, in all three figures are indicated, in dotted lines, the approximate curves which would have been observed if only the changing declination of the sum had been responsible for variations in intensity. These curves were computed from the air masses at Tucson, and the

(upper curve of fig. 1) shows no resemblance to the curve of average atmospheric transmission. The upper curves of Figure 2, for green radiation at 9:00 a. m. and 3:00 p. m., very roughly resemble, in general shape, the curves of average atmospheric transmission. Maximal intensities occur, on the average, about two months before the summer solstice, while minimal intensities occur at or very near the winter solstice. The curves of average intensity (three upper curves of fig. 3) exhibit these features clearly. The unexpectedly low values extending throughout almost the entire interval from June to September, inclusive, are especially noticeable. The green radiation is of nearly equal average intensity at 9:00 a. m. and at 3:00 p. m. throughout the year.

The intensity curves for ultraviolet at wave length 0.32μ resemble, in general shape, the corresponding curves

[1] These are (approximately) the curves we should expect if only the changing declination of the sun affected the intensity by varying the air mass traversed by the radiation.

of average atmospheric transmission much more closely than do the curves for green radiation, as is to be expected. Here again the maxima occur earlier than the transmission curves would indicate, averaging, on the curve for 12:00 noon, from one to two months earlier than the summer solstice and about one month earlier on the curves for 9:00 a.m. and 3:00 p. m. In all cases the minima occur at or very near, the winter solstice. A marked reduction in intensity appears in the interval from June to September, as has been noted in the case of the green radiation also. The intensity at 0.32μ at 3:00 p. m. generally falls below that at 9:00 a. m., the average difference being about 5 per cent. During the last four months of the year the average difference is only about 1 per cent.

green or the ultraviolet to vary by 10 to 30 per cent or more within the space of a few days. As a rule, variations at the shorter wave length are relatively larger than at the longer wave length.

Corresponding curves for barometric pressure, temperature, absolute humidity, and provisional sun-spot numbers (Zürich, reported by the Carnegie Institution of Washington) also are shown in Figure 4 to illustrate the lack of correlation observed in general between these factors and the radiant intensity. Absolute humidity seemed to show a slight inverse correlation with the radiation values. No correlation between sun-spot numbers and radiant intensity could be discovered, considering as a whole the evidence shown by curves for the entire

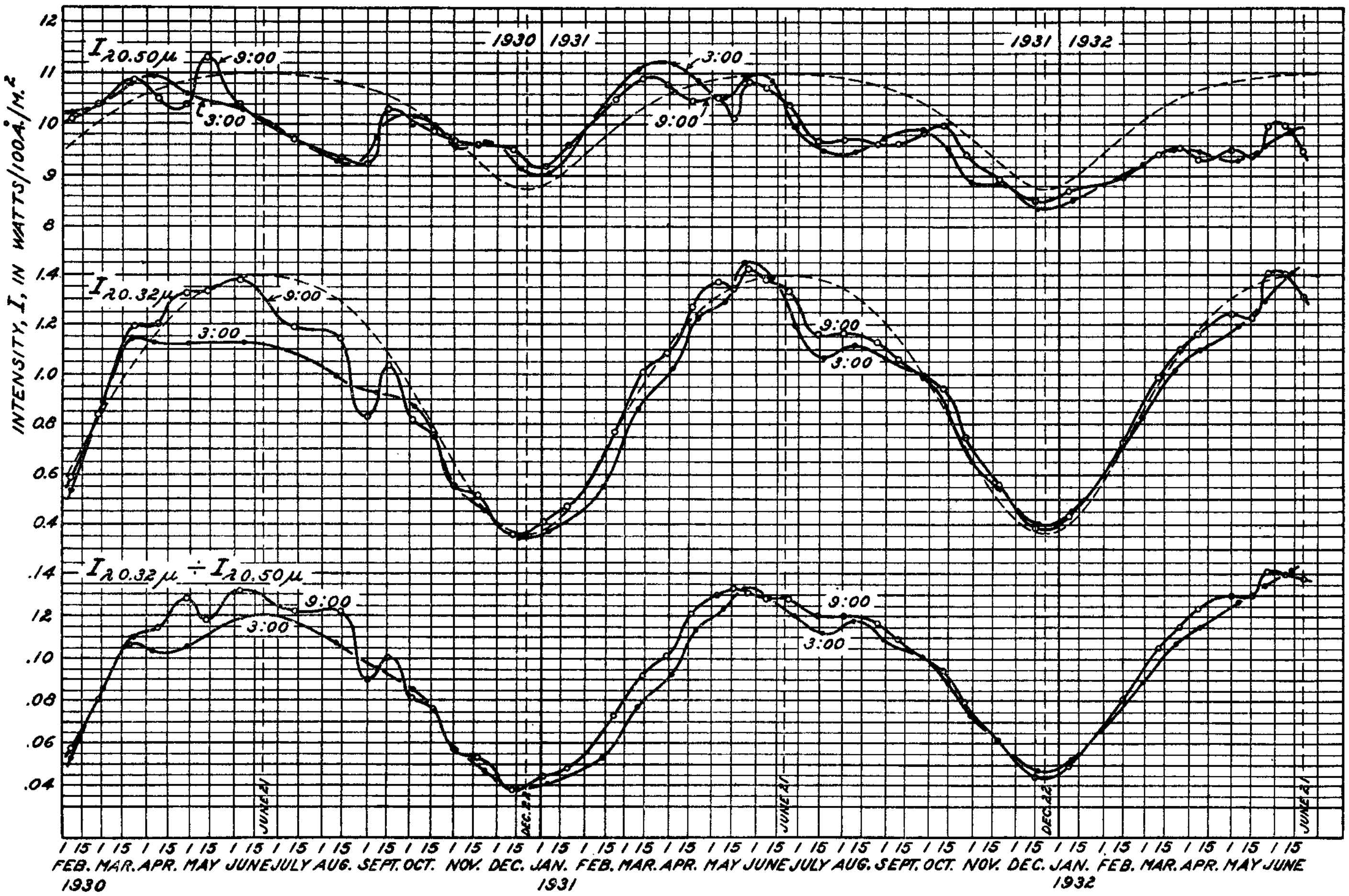

FIGURE 2.—Intensity of solar radiation at wave lengths 0.50μ and 0.32μ, at 9:00 a. m. and 3:00 p. m., local apparent time. Each plotted point is the average of 10 daily values. The dotted lines are the calculated curves of average atmospheric transmission.[1] The lower curves represent the ratios of the intensity at λ0.32μ to that at λ0.50μ.

The lower curves of Figures 2 and 3, which represent the ratios of the intensity at λ0.32μ to the intensity at λ0.50μ, closely resemble the corresponding curves for λ0.32μ except along a portion of the curve for 12:00 noon. The above notes in regard to the shapes of the curves for λ0.32μ therefore apply to these curves also.

Surprisingly large day-to-day variations in the intensity values were frequently observed at both wave lengths. These variations are illustrated in Figure 4, in which the galvanometer readings for 12:00 noon are plotted for September, 1930, and for May, 1931. These readings are proportional to the intensity. The ratios of the readings are shown also (curve B÷A). As illustrated by these curves, it is not uncommon for the intensity in either the

29 months. Almost no correlation is evident between barometric pressure and radiation, or between temperature and radiation, if all the data are considered.

Atmospheric haze, observed in the manner described, was found to be accompanied usually by somewhat lower radiation values. Separating all the observed densities of haze into two groups, designated "faint" and "dense," it was found that when "faint" haze was observed the intensities at 0.50μ and at 0.32μ were reduced, on the average, by about 2 per cent and 5 per cent, respectively. The corresponding reductions at "dense" haze averaged about 4 per cent and 8 per cent.

DISCUSSION

The irregularities shown by the curves of radiant intensity appear to represent actual variations in the

[1] These are (approximately) the curves we should expect if only the changing declination of the sun affected the intensity by varying the air mass traversed by the radiation.

radiation reaching the earth at Tucson. Undoubtedly the readings are affected to some extent by instrumental errors, due particularly to the effects of temperature variations on the effective sensitivity of the solar radiometer. Both the thermoelectric power and the ohmic resistance vary with the temperature, the variations being opposite in effect. In the instrumental arrangement we have used the net effect of these two variations is not zero. However, it is seen by reference to the curves that the ratio of the intensities at λ 0.32μ and 0.50μ also show marked fluctuations similar to those in the radiation curve for 0.32μ. Since the readings at the two wave lengths should be affected to very nearly the same extent perature, and possibly other factors. In general these are not independent phenomena. Therefore they affect the radiant intensity in a complicated manner and it is difficult to discover the contribution of each to the net effect. For this reason the general lack of correspondence observed between radiant intensities and barometric pressure, temperature, humidity or sun-spot numbers, illustrated in Figure 4, is not conclusive proof of lack of correspondence. The effects of accompanying phenomena tend to mask the correlation between radiation values and the particular phenomenon under consideration. We have shown, however, that visible haze in the lower atmosphere generally is accompanied by lower radiant intensi-

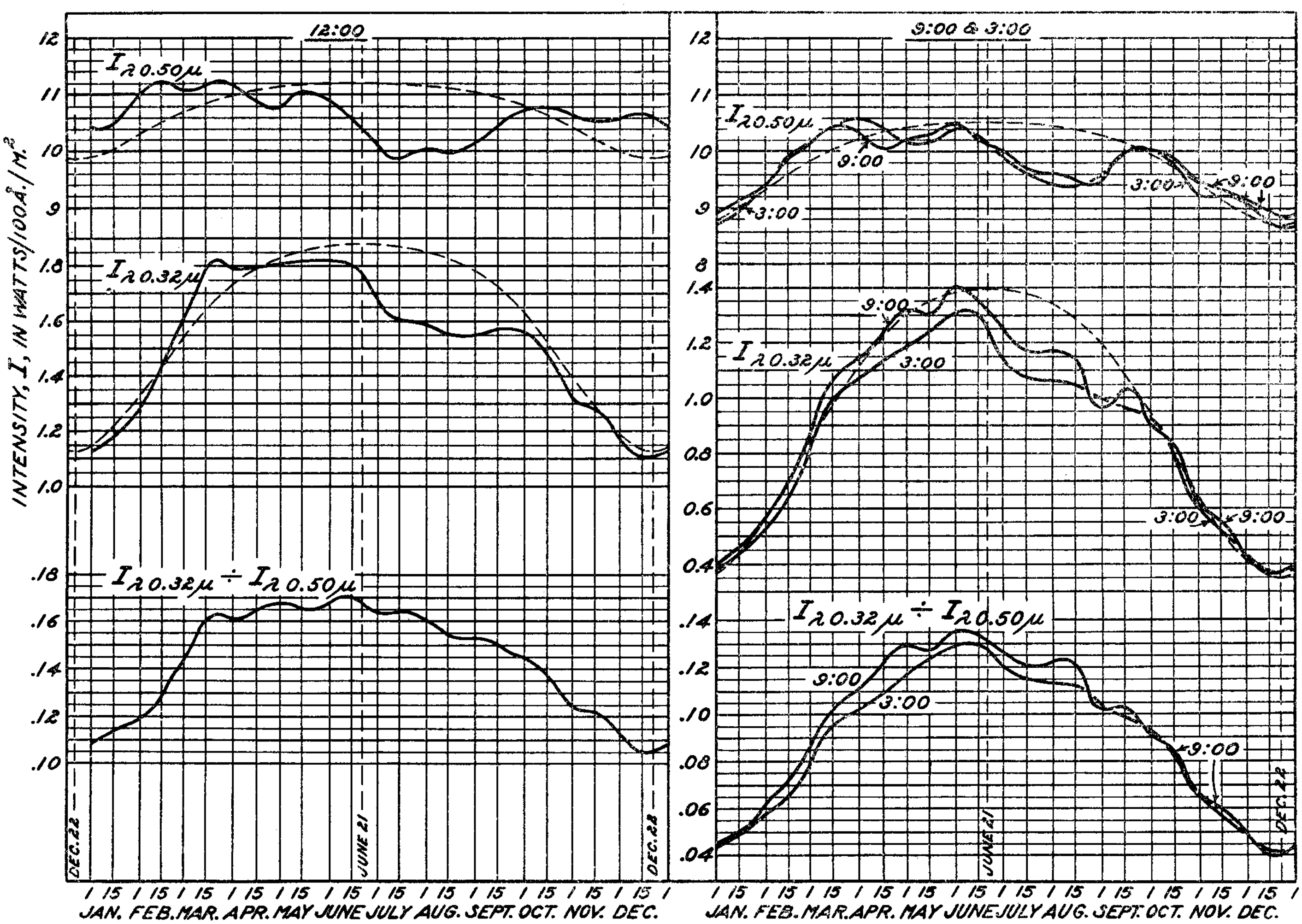

FIGURE 3.—Average values of solar radiation at wave lengths 0.50μ and 0.32μ, from the smooth curves of Figures 1 and 2. Three-year averages, February to June, inclusive; two-year averages, July to January, inclusive. The dotted lines are the calculated curves of average atmospheric transmission.[1]

by changes in temperature, the irregular variations in the ratio of intensities could not be due in any appreciable degree to temperature effects. This we consider clear evidence that the observed fluctuations in radiant intensity are mostly real, not observational, in origin. This is indicated also by the lack of correspondence between the curves showing daily values of radiation and of temperature.

Several factors probably are each responsible, in part, for the irregularities in the radiation curves, namely, variations in the intensity of radiation emitted by the sun, atmospheric humidity, dust and haze, barometric pressure, invisible cloud films, atmospheric ozone, temperature—

ties. A slight correspondence was noted also in the case of absolute humidity. It would seem that the observed variations in intensity frequently are too great to be attributed to meteorological and instrumental effects alone. This suggests that the emission of radiation from the sun may vary appreciably at the observed wave lengths.

Pettit (2) has computed from measurements at Mount Wilson, Calif., the ratios of intensity of solar radiation at λ 0.32μ to the intensity at λ 0.50μ, for air mass zero, from the middle of 1924 to the latter part of 1931. He finds considerable correlation between the curve of monthly averages of these values and the curve representing monthly averages of numbers of sun-spot groups, except during the year from June, 1928, to June, 1929. This

[1] These are (approximately) the curves we should expect if only the changing declination of the sun affected the intensity by varying the air mass traversed by the radiation.

does not necessarily mean that a similar correspondence should hold for radiation whose intensity has been reduced by passage through the atmosphere. At Tucson the air mass traversed by the sun's rays at noon varies during the year from 0.93 to 1.63 (zenith mass at sea level = 1.00), while the masses at 9:00 a.m. and 3:00 p.m. vary from 1.20 to 2.72. Hence atmospheric effects may almost completely mask the correlation with sun-spot numbers, as seems to be the case for our data. Pettit's sun-spot curve (loq.cit., fig. 4) from February, 1930, to September, 1931, shows no correspondence with our curves for radiation at λ 0.32 during the same period.

Although no data on the effect of invisible cloud films is at hand, it is probable that such films over the sun may effectively reduce the solar radiation, accounting partially for some of the low values observed under an apparently unclouded sun.

The low radiation values observed from June to September may be correlated directly or indirectly with the rains which occur in that period. More than half of the annual rainfall at Tucson occurs in the four months June to September, with the heaviest rainfall in July and August. The coincidence in point of time between this rainy season and the midsummer drop in radiation is very close. This sag in the curves probably is the reason why maximal intensities are observed, on the average, from one to two months earlier than the summer solstice, while minimal intensities occur at, or very near, the winter solstice, as expected.

We believe, particularly in view of the relative clearness of the atmosphere of southern Arizona, that the marked fluctuations in radiation which we have observed are not peculiar to this region. Without doubt fluctuations of similar or greater magnitude would be revealed by similar measurements elsewhere. The few data thus far reported by other observers support this conclusion.

Certain facts are worth noting by the heliotherapist. First, the marked day-to-day variations necessitate that measurements of radiant intensity be made simultaneous with the exposure of the patient, in case sufficiently accurate data on the physiological effects of radiation shall have been obtained to warrant accurately regulated dosage. The variations of intensity at wave-lengths shorter than 0.32μ should be expected to be even greater than at this wave length. Curves of average intensity such as those in Figure 3 can not be used to predict, except very roughly, the radiation value for any particular day. Departures from these curves, amounting not infrequently to 30 per cent or more, may occur on any day.

Second, no accurate idea of the intensity of solar radiation on any given day can be deduced from observations of sun-spot numbers, atmospheric humidity, barometric pressure, temperature, or haze. Third, the seasonal variations in intensity are greater for the shorter wave lengths of the ultraviolet spectrum than for longer wave lengths. The average curves in Figure 3 may be used as rough guides in determining relative exposure times at various seasons, so far as the spectral regions near wave lengths 0.32μ and 0.50μ are concerned. These remarks apply to direct radiation only from an unclouded sun. A considerable amount of indirect radiation may be received from the sky and from clouds.

SUMMARY

Intensities of direct solar radiation at wave lengths 0.50μ and 0.32μ were measured at Tucson, Ariz., over a period of 29 months, from February, 1930, to June, 1932, inclusive. Intensities are reported for the hours 9:00 a.m., 12:00 noon, and 3:00 p.m. under an unclouded sun. Average intensities are plotted in absolute units; also in relative values at the two wave lengths. The curves show striking fluctuations at irregular intervals and marked departures from the curves, which should be observed if the declination of the sun were the only variable factor. Maximal intensities at both wave lengths occur, on the

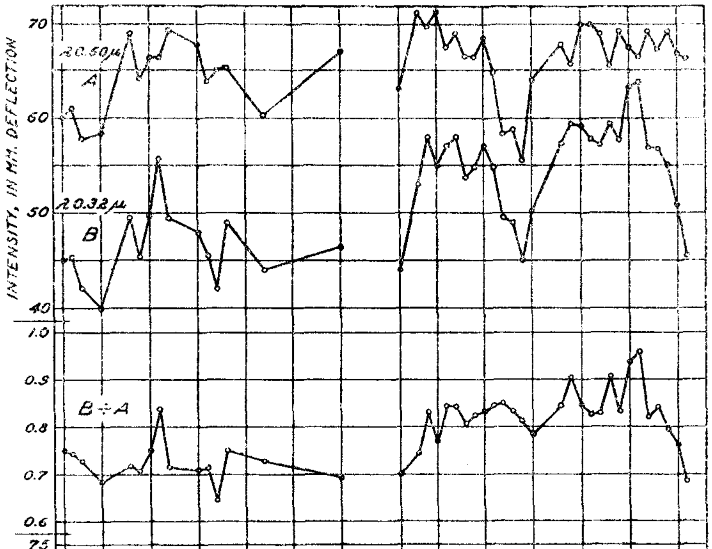

FIGURE 4.—Illustrating the marked variations in intensity of solar radiation (upper three curves), also the general lack of correlation of radiant intensity with sun-spots and various meteorological phenomena.

average, from one to two months earlier than the summer solstice, seemingly because of a midsummer decrease in radiation coincident with the rainy season. Minimal intensities are observed at the winter solstice, as expected. Large day-to-day variations in intensity occur at both wave lengths. In general these variations show very little correspondence with either sun-spot numbers, absolute humidity, air temperature, or barometric pressure, considered separately.

Pettit has demonstrated a striking correspondence between sun-spot numbers and the intensity of solar radiation above the atmosphere at wave length 0.32μ. No such correlation is found for radiation after passing through the atmosphere above Tucson. Haze in the lower atmosphere usually is accompanied by somewhat lowered radiation values. In the practice of heliotherapy. it is important to recognize the probability of frequent intensity variations of considerable magnitude. Only a very rough prediction of radiation values on any given day can be made by reference to average values previously found. Accurate dosage can be determined only from radiation measurements made at the time of exposure of the patient.

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CHANGES IN THE SOLAR CONSTANT OF RADIATION

By Prof. Dr. FRANZ BAUR

[Staatl. Forschungsstelle für langfristige Witterungs-vorhersage, Frankfurt on the Main, Germany, February 14, 1932]

SYNOPSIS

In the first part (A) of this paper it is shown that even the latest solar constant observations of the Smithsonian Institution contains a 12-month period, and that its course is exactly the reverse of what it was before the alteration was made in the formula used for the determination of the transparency of the atmosphere. In the second part (B), the changes in the solar constant from 1919–1932, according to Abbot's measurements, are recorded against the sun-spot changes. It seems that the changes in the solar constant are neither parallel to nor opposed to those of the sun spots. But the highest values of the solar constant appear chiefly to occur *between* the maxima and minima of sun spots, whilst the lowest values occur near the extremes of sun-spot activity. An attempt is made to explain this. In the third part (C) of the work it is pointed out that a similar relationship exists between certain weather phenomena and sun spots.

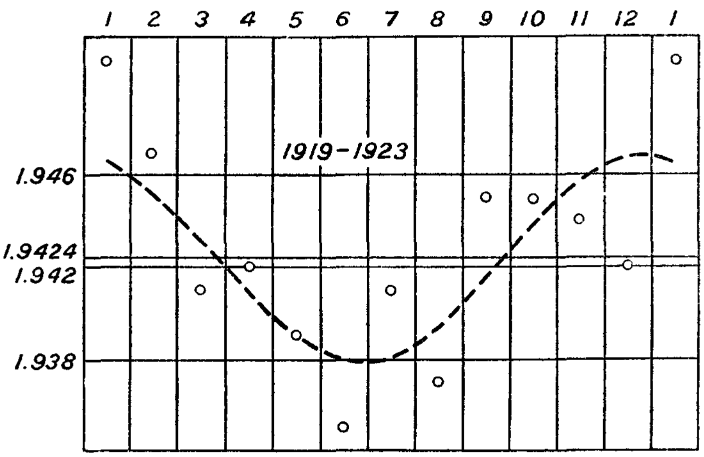

FIGURE 1.—Five-year averages of the mean monthly values of the solar constant. 1919–1923. Circles indicate averages of observed values; the dotted line is a sign curve of approximate fit through these values

A. THE ANNUAL VARIATION OF ABBOT'S SOLAR CONSTANT

In the following, only the large changes of the solar constant, as expressed in the monthly means, are considered.

C. F. Marvin[1] proved, as is known, that in the monthly means of the values of the solar constant of 1919 to July, 1924 (according to Abbot and his fellow workers), a definite 12-month periodicity occurs. From this it must be concluded that the values estimated by means of a so-called "short method" (in use since 1919) are also *still affected by terrestrial influences.* Since Abbot, however, has reckoned[2] the transparency of the atmosphere, using his short method (since 1925 according to a new formula), the question arises as to whether the disturbing effects of terrestrial conditions on the measurements thus have been eliminated.

The recent publication[3] of the monthly means of the solar constant values from 1919 to 1930 does not show whether or not the former values have been adapted to the new formula for the determination of the transparency of the atmosphere. But Abbot says in this work that the best values are those from January, 1924, onward. He evidently assumes that the beginning of the year 1924 marks a break in the homogeneity of the measurements. I examined therefore the annual variation of the solar constant separately for the periods 1919–1923 and 1924–1930. The result is shown in Figures 1 and 2. It is seen that in the period 1924–1930 an annual variation also occurs which can readily be shown by a sine curve. But the course of the annual variation in the second period of time is exactly the reverse of that in the first.

On the other hand, it also becomes apparent, from the comparison of Figures 1 and 2, that the amplitude of the annual changes in Abbot's solar constant since the use of the new formula has become smaller. Of course, this lessening of the annual amplitude is probably chiefly caused by the standard deviation of the monthly means in the solar constant values in the period 1924–1930, being in itself smaller than that in the period 1919–1923.

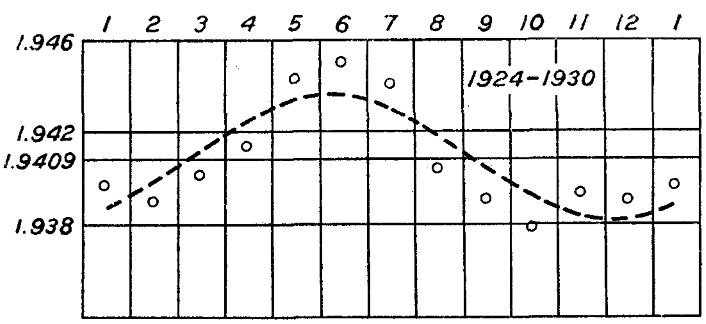

FIGURE 2.—Seven-year averages of the mean monthly values of the solar constant, 1924–1930. Circles indicate averages of observed values; the dotted line is a sign curve of approximate fit through these values

In the following summary the size of the annual change, expressed by means of the difference between the mean value of the six months from September to February and that of the six months from March to August, is compared with the size of the standard deviation in the corresponding period of time as well as with the presumably accidental annual change in the relative numbers of sun spots.

[1] C. F. Marvin, Monthly Weather Review 53 (1925), p. 301.

[2] C. G. Abbot, Gerlands Beiträge zur Geophysik 16, 1927, pp. 362 and 363.

[3] Smithsonian Misc. Collect. 85, No. 1. Washington 1931.